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Neutrinos and Supernovae

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Neutrinos and Supernovae

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Motivation

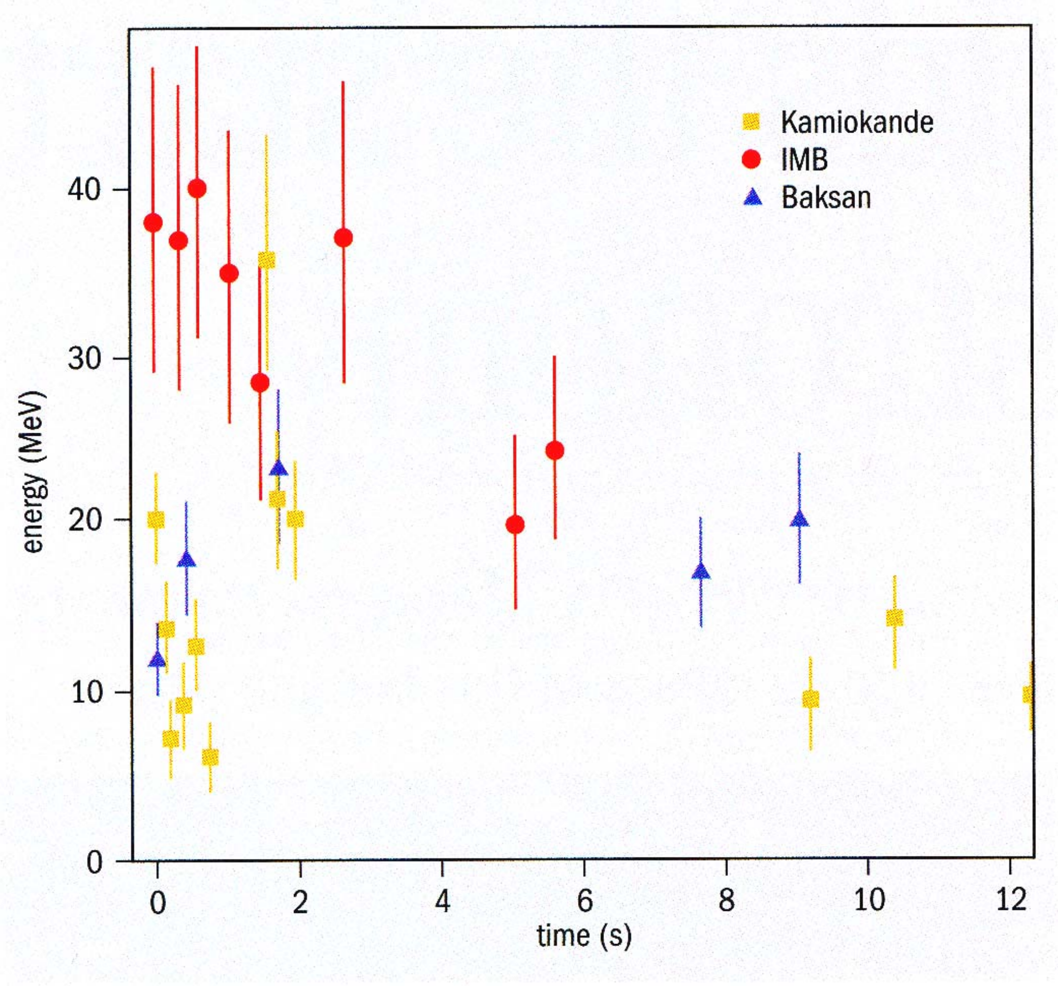
Neutrinos are the most enigmatic particles in the Universe

Associated with some of the long standing problems in astrophysics

- Solar neutrino deficit
- Formation of structure in the Universe
- Supernovae II (SNe II)
- Stellar/Neutron Star core cooling
- Dark Matter/Dark Energy

Intensities in excess of 10^{30} W/cm^2 and luminosities up to 10^{53} erg/s

Extra Solar Neutrinos



1st observation of neutrinos from outside solar system 1987

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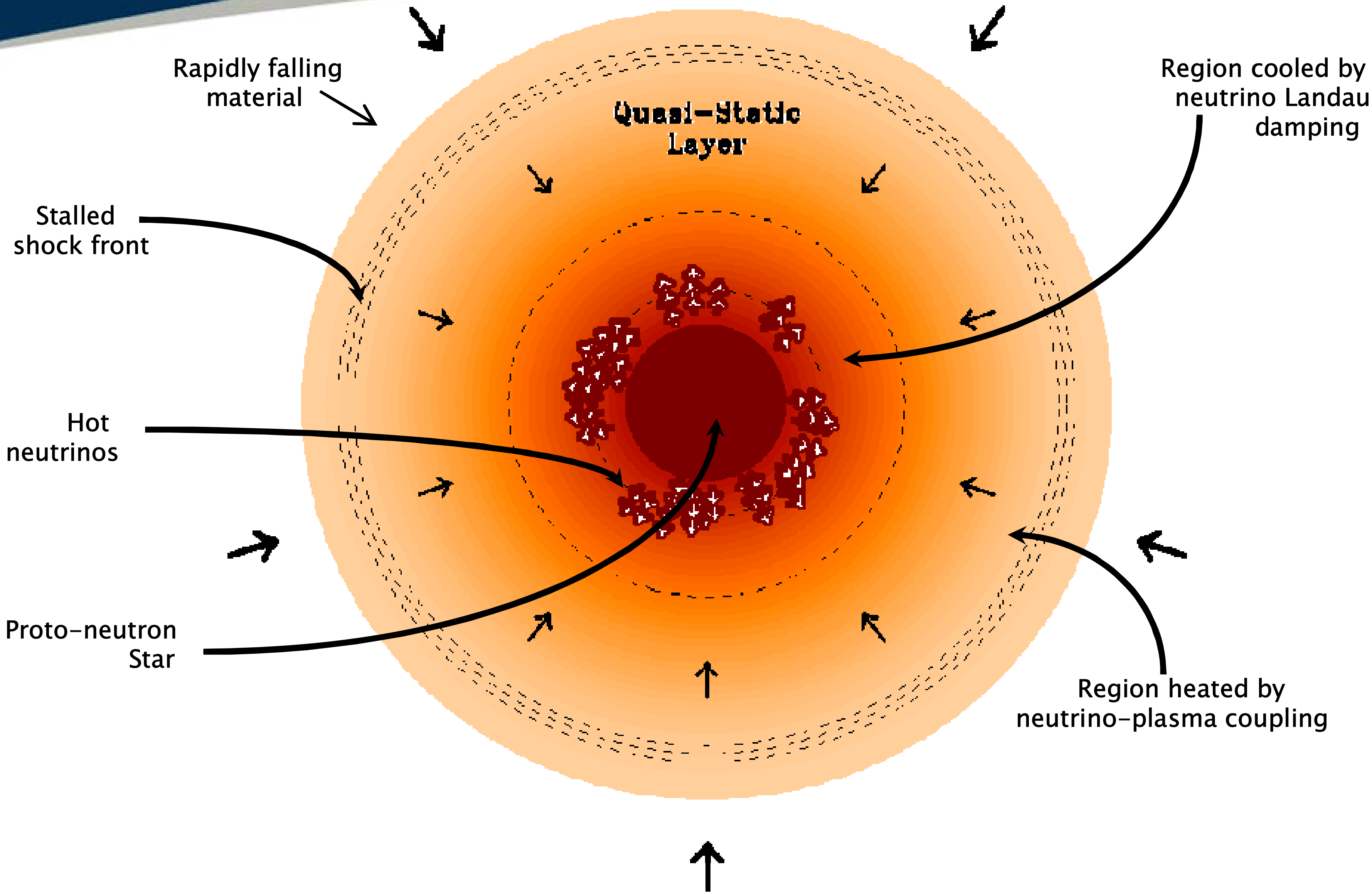
Supernovæ Explosion



Supernova Explosion

A supernova releases 5 $\times 10^{53}$ erg
(gravitational binding energy of the original star)

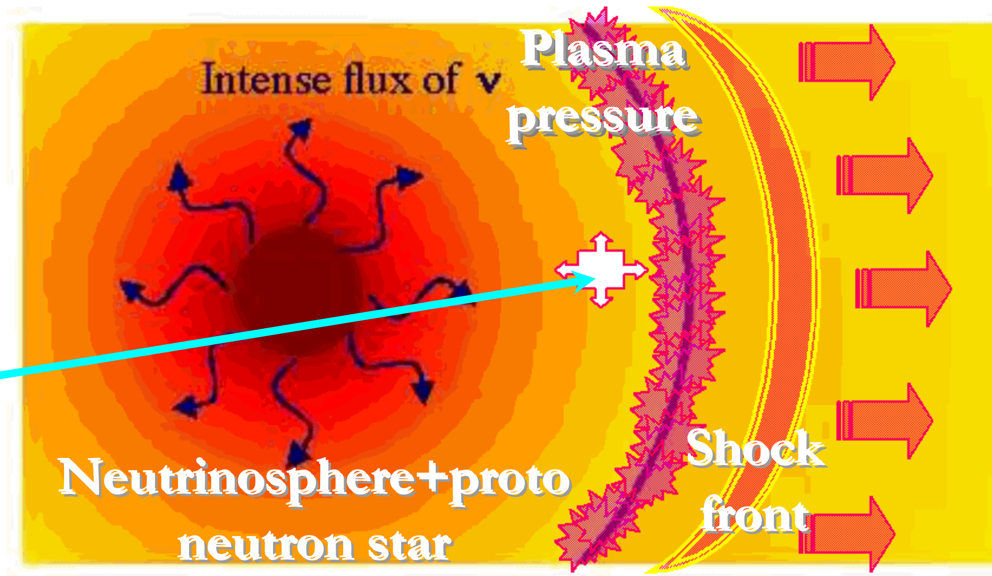
• neutrinos 99 % •

• kinetic energy+light ~ 10^{51} erg •

How to turn an implosion into an explosion?

$\Rightarrow$ Neutrino-plasma scattering instabilities in dense plasmas

Neutrino-plasma heating



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Neutrino Refractive Index

The interaction can be easily represented by neutrino refractive index.

The dispersion relation: $(E_\nu - V)^2 - p_\nu^2 c^2 - m_\nu^2 c^4 = 0$ (Bethe, 1986)

E is the neutrino energy, p the momentum, m_ν the neutrino mass.

The potential energy $V = \sqrt{2} G_F n_e$

G_F is the Fermi coupling constant, n_e the electron density

$\Rightarrow$ Refractive index

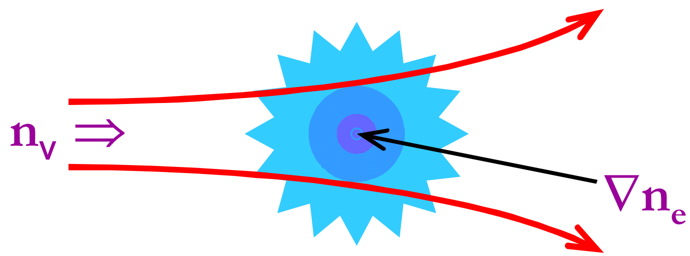
$$N_\nu = \left(\frac{ck_\nu}{\omega_\nu} \right)^2 = \left(\frac{cp_\nu}{E_\nu} \right)^2$$

$$N_\nu \cong 1 - \frac{2\sqrt{2} G_F}{\hbar k_\nu c} n_e$$

Note: cut-off density $n_{ec} > \dfrac{\varepsilon_\nu}{2\sqrt{2} G_F}$

ε_ν neutrino energy

Electron neutrinos are refracted away from regions of dense plasma - similar to photons.



Neutrino Ponderomotive Force

For intense neutrino beams, we can introduce the concept of the Ponderomotive force to describe the coupling to the plasma. This can then be obtained from the 2nd order term in the refractive index.

Definition

$$\mathrm{F}_{POND} = \frac{N-1}{2}\nabla\xi$$

[Landau & Lifshitz, 1960]

where ξ is the energy density of the neutrino beam.

$$N = 1 - \frac{2\sqrt{2}G_F}{\varepsilon_\nu}n_e \quad \Rightarrow \quad \mathrm{F}_{\mathrm{Pond}} = -\frac{\sqrt{2}G_F n_e}{\varepsilon_\nu}\nabla\xi$$

n_ν is the neutrino number density.

$$\boxed{\mathrm{F}_{\mathrm{Pond}} \equiv -\sqrt{2}G_F n_e \nabla n_\nu}$$

Bingham *et al*., 1997.

Neutrino Dynamics in Dense Plasma

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Dynamics governed by Hamiltonian (Bethe, '86):

$$H_{eff} = \sqrt{\mathbf{p}_\nu^2 c^2 + m_\nu^2 c^4} + 2G_F n_e(\mathrm{r},t)$$

G_F - Fermi constant
n_e - electron density

¶ Effective potential due to **weak interaction** with background electrons
¶ Repulsive potential

$$\mathbf{F} = -\sqrt{2}G_F \nabla n_e(\mathrm{r},t)$$

Force on a single neutrino due to electron density modulations

Neutrinos bunch in regions of lower electron density

$$\mathbf{F}_{pond} = -\sqrt{2}G_F \nabla n_\nu(\mathrm{r},t)$$

Force on a single electron due to neutrino distribution

Ponderomotive force* due to neutrinos pushes electrons to regions of lower neutrino density

* ponderomotive force derived from semi-classical (L.O.Silva et al, '98) or quantum formalism (Semikoz, '87)

Neutrino Ponderomotive Force (2)

Force on one electron due to electron neutrino collisions f_{coll}

$$f_{coll} = \sigma_{\nu_e} \xi \qquad \sigma_{\nu_e} = \left(\frac{G_F k_B T_e}{2\pi\hbar^2 c^2} \right)^2$$

$\sigma_{\nu e}$ is the neutrino-electron cross-section

Total collisional force on all electrons is

$$\mathrm{F}_{\mathrm{coll}} = n_e f_{coll} = n_e \sigma_{\nu_e} \xi$$

$$\frac{\mathrm{F}_{\mathrm{Pond}}}{\mathrm{F}_{\mathrm{coll}}} = \frac{\sqrt{2\pi}\,\hbar^3 c^3}{G_F k_B^2 T^2} \frac{|k_{Mod}|}{k_\nu}$$

$|k_{mod}|$ is the modulation wavenumber.

For a 0.5 MeV plasma $\qquad \dfrac{\mathrm{F}_{\mathrm{Pond}}}{\mathrm{F}_{\mathrm{coll}}} \approx 10^{10}$

$\sigma_{\nu e} \Rightarrow$ collisional mean free path of 10^{16} cm.

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Supernova II Physical Parameters

To form a neutron star 3×10^{53} erg must be released

(gravitational binding energy of the original star)

• light+kinetic energy ~ 10^{51} erg •

• gravitational radiation < 1% •

• neutrinos 99 % •

¶ Electron density @ 100-300 km: $n_{e0} \sim 10^{29} - 10^{32}$ cm^{-3}

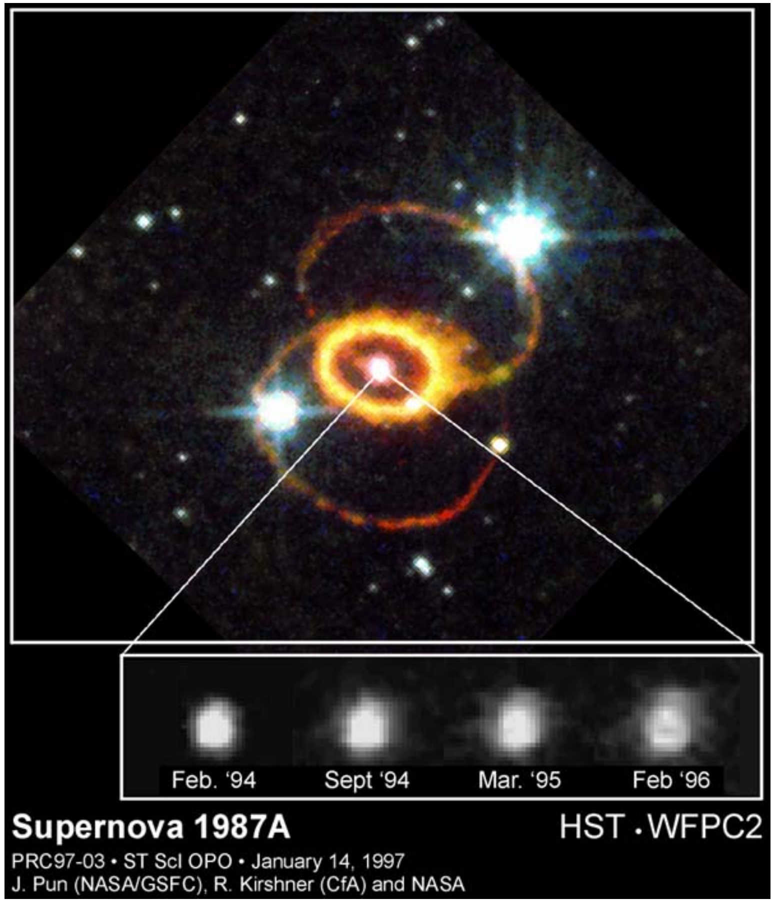
¶ Electron temperature @ 100-300 km: $T_e \sim 0.1 - 0.5$ MeV

¶ ν_e luminosity @ neutrinosphere~ $10^{52} - 5\times10^{53}$ erg/s

¶ ν_e intensity @ 100-300 Km ~ $10^{29} - 10^{30}$ W/cm^2

¶ Duration of intense ν_e burst ~ 5 ms
(resulting from $p+e \rightarrow n+\nu_e$)

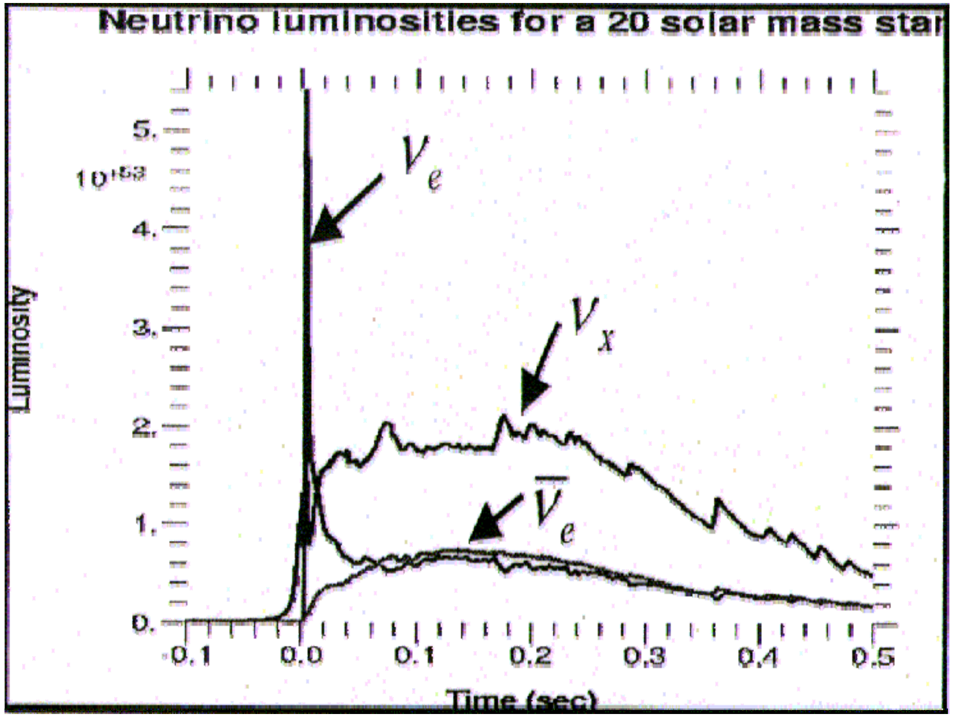
¶ Duration of ν emission of all flavors ~ 1 - 10 s



Neutrino heating is necessary for a strong explosion

The shock exits the surface of the proto-neutron star and begins to stall approximately 100 milliseconds after the bounce.

The initial electron neutrino pulse of 5×10^{53} ergs/second is followed by an "accretion" pulse of all flavours of neutrinos.



This accretion pulse of neutrinos deposits energy behind the stalled shock, increasing the matter pressure sufficiently to drive the shock completely through the mantle of the star.

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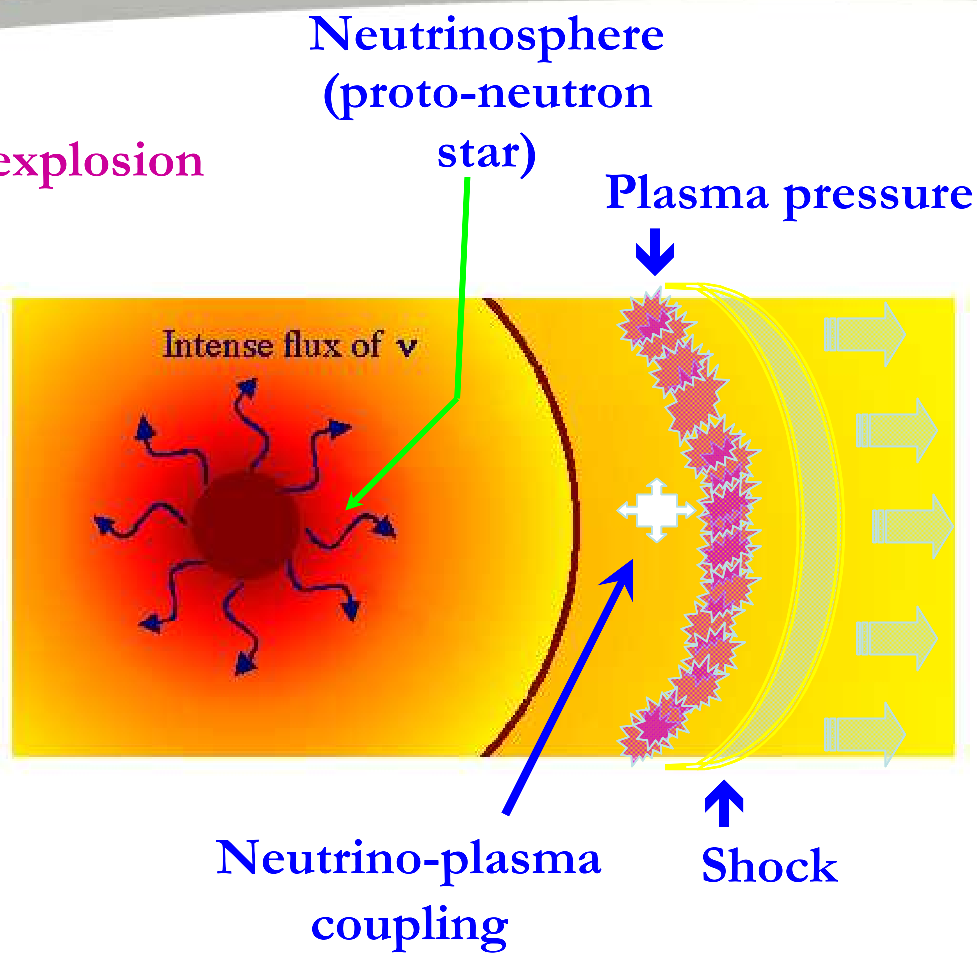
Supernova Explosion

- **How to turn an implosion into an explosion**
  - New neutrino physics
  - λ_{mfp} for eν collisions ~ 10^{16} cm in collapsed star
  - λ_{mfp} for collective plasma-neutrino coupling ~ 100m

- **How?**
  - New non-linear force — neutrino ponderomotive force
  - For intense neutrino flux collective effects important
  - Absorbs 1% of neutrino energy
    $\Rightarrow$ sufficient to explode star



Bingham *et al*., **Phys. Lett. A**, 220, 107 (1996)
Bingham *et al*., **Phys. Rev. Lett.**, 88, 2703 (1999)

Electroweak plasma instabilities

Two stream instability

- **Neutrinos driving electron plasma waves** $v_\phi \sim c$
- **Anomalous heating in SNe II**

Collisionless damping of electron plasma waves

- **Neutrino Landau damping**
- **Anomalous cooling of neutron stars**

Electroweak Weibel instability

- **Generation of quasi-static B field**
- **Primordial B and structure in early Universe**

Neutrino kinetics in a dense plasma

Kinetic equation for neutrinos

(describing neutrino number density conservation / collisionless neutrinos)

$$\frac{\partial f_\nu}{\partial t} + \mathbf{v}_\nu \cdot \frac{\partial f_\nu}{\partial \mathbf{r}} - \sqrt{2} G_F \left(\nabla n_e(\mathrm{r}, t) + \frac{1}{c^2} \frac{\partial \mathbf{J}_e(\mathrm{r}, t)}{\partial t} - \frac{\mathbf{v}_\nu}{c} \times \nabla \times \frac{\mathbf{J}_e(\mathrm{r}, t)}{c} \right) \cdot \frac{\partial f_\nu}{\partial \mathbf{p}_\nu} = 0$$

Kinetic equation for electrons driven by neutrino pond. force

(collisionless plasma)

$$\frac{\partial f_e}{\partial t} + \mathbf{v}_e \cdot \frac{\partial f_e}{\partial \mathbf{r}} - \sqrt{2} G_F \left(\nabla n_\nu(\mathrm{r}, t) + \frac{1}{c^2} \frac{\partial \mathbf{J}_\nu(\mathrm{r}, t)}{\partial t} - \frac{\mathbf{v}_e}{c} \times \nabla \times \frac{\mathbf{J}_\nu(\mathrm{r}, t)}{c} \right) \cdot \frac{\partial f_e}{\partial \mathbf{p}_e} - e\left(\mathbf{E} + \frac{\mathbf{v}_e}{c} \times \mathbf{B} \right) \cdot \frac{\partial f_e}{\partial \mathbf{p}_e} = 0$$

+

Maxwell's Equations

(Silva et al, ApJ SS 1999)

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Two stream instability driven by a neutrino beam

Usual perturbation theory over kinetic equations + Poisson's equation

$$n_e = n_0 + n_{e1} \qquad f_e = f_{e0}(\mathbf{p}_e) + f_{e1}$$

$$\mathbf{v}_e = \mathbf{v}_1 \qquad f_\nu = f_{\nu 0}(\mathbf{p}_\nu) + f_{\nu 1}$$

$$\mathbf{v}_\nu = \mathbf{v}_{\nu 0} + \mathbf{v}_{\nu 1} \qquad \mathbf{E} = \mathbf{E}_1$$

Dispersion relation for electrostatic plasma waves

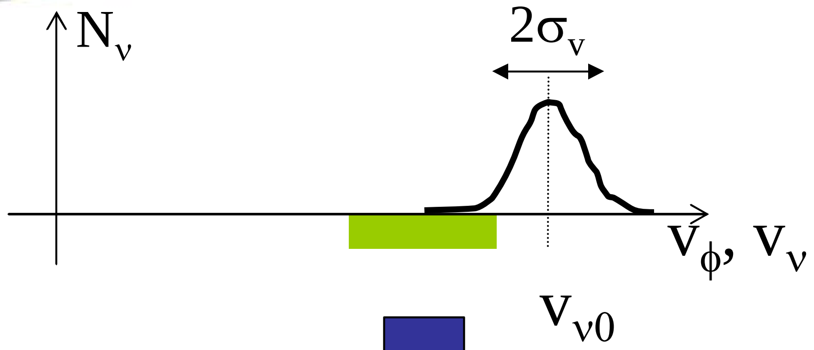
$$1 + \chi_e(\omega_L, \mathbf{k}_L) + \chi_\nu(\omega_L, \mathbf{k}_L) = 0$$

Electron susceptibility **Neutrino susceptibility**

$$\chi_\nu(\omega_L, \mathrm{k}_L) = -2\, G_F^2 \frac{k_L^3 n_{e0} n_{\nu 0}}{m_e \omega_{pe0}^2} \left(1 - \frac{\omega_L^2}{c^2 k_L^2}\right)^2 \chi_e \int d\mathbf{p}_\nu \frac{\mathbf{k}_L \cdot \dfrac{\partial \hat{f}_{\nu 0}}{\partial \mathbf{p}_\nu}}{\omega_L - \mathbf{k}_L \cdot \mathbf{v}_\nu}$$

(Silva et al, PRL 1999)

Instability Regimes: hydrodynamic vs kinetic



If region of unstable PW modes **overlaps** neutrino distribution function **kinetic regime becomes important**

Unstable PW modes **(ω_L,k_L)**

$N_{e0} = 10^{29}$ cm^{-3}	$\langle E_\nu \rangle$ =10 MeV
$L_\nu = 10^{52}$ erg/s	T_ν = 3 MeV
R_m = 300 Km	m_ν = 0.1 eV

Kinetic instability $\gamma \propto G_F^{\,2}$ **if** $\left| \frac{\omega_L}{k_L} - v_{\nu 0} \right| << \sigma_{v_\nu}$

Hydro instability $\gamma \propto G_F^{\,2/3}$ **if** $\left| \frac{\omega_L}{k_L} - v_{\nu 0} \right| >> \sigma_{v_\nu}$

$$\sigma_{v_\nu} / c \approx \mathbf{10^{-16}}$$

$$\left| \frac{\omega_L}{ck_L} - \frac{v_{\nu_0}}{c} \right| \approx \frac{\gamma_{\max}}{\omega_{pe0}} \beta_\phi \approx \mathbf{10^{-14} - 10^{-11}}$$

where $v_\nu = p_\nu c^2/E_\nu = p_\nu c^2/(p_\nu^2 c^2 + m_\nu^2 c^4)^{1/2}$

- for $m_\nu \to 0$, $\sigma \to 0$ **hydro regime** -

Estimates of the Instability Growth Rate

$n_{e0}=10^{29}$ cm^{-3}
$L_\nu = 10^{52}$ erg/s
$R_m = 300$ Km
$\langle E_\nu \rangle=10$ MeV

Growth distance ~ 1 m
(without collisions)

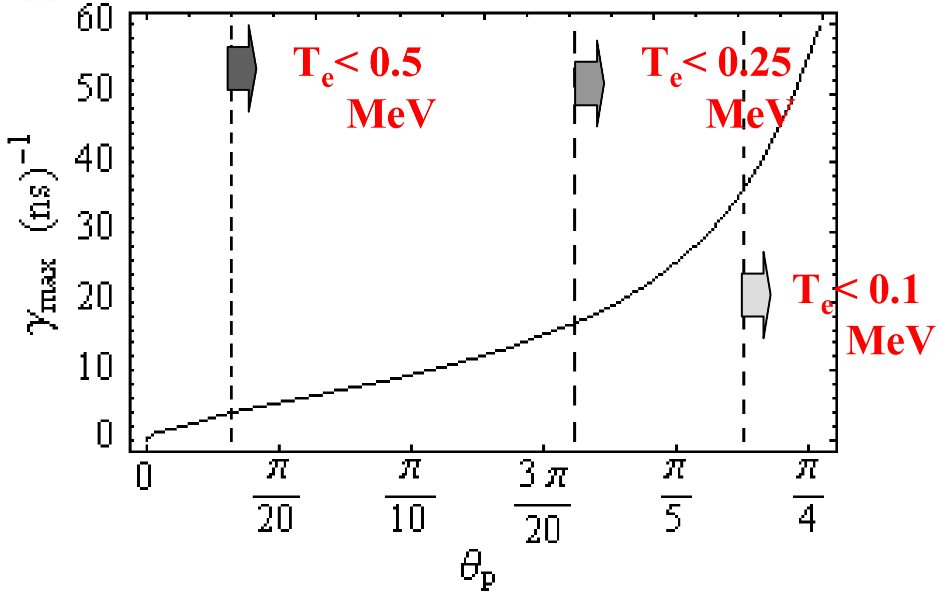
Growth distance ~ 300 m
(with collisions)

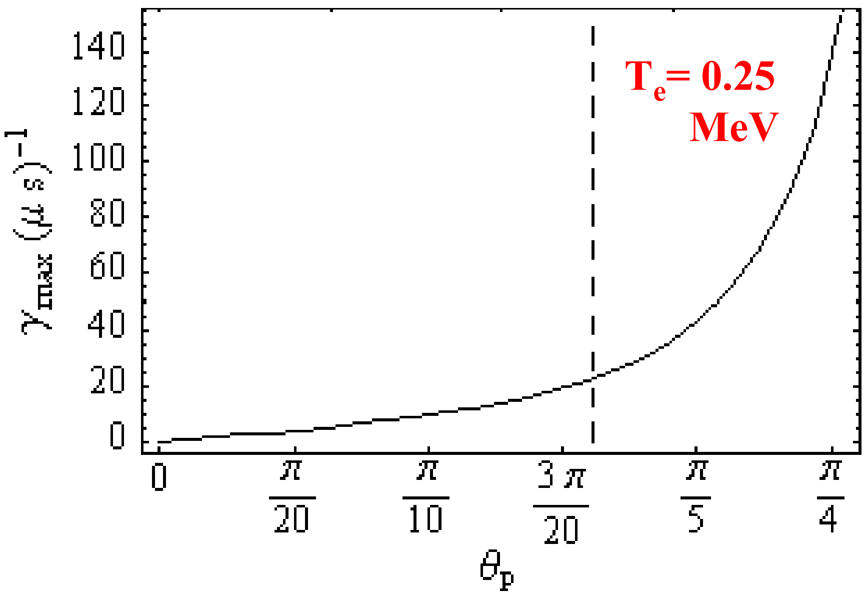
- 6 km for 20 e-foldings -

Mean free path for
neutrino electron single scattering
~ 10^{11} km

Single ν-electron scattering $\propto G_F^2$

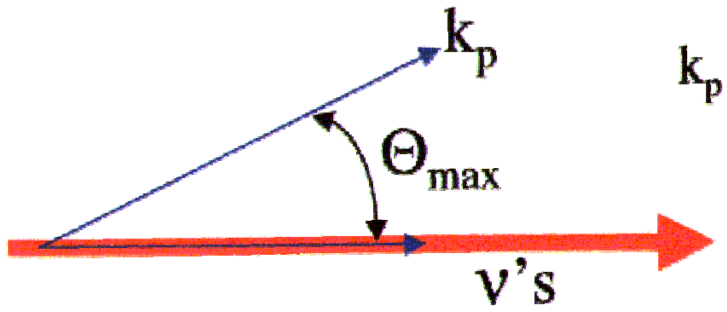
Collective mechanism much stronger than single particle processes





Saturation Mechanism

Neutrino streaming instability saturates by electron Landau damping



$k_p \sim \omega_{pe0}/c \cos\Theta$ $\qquad$ $\Theta_{max} \sim \arccos(v_{th}/c)$

$T_e \uparrow \Rightarrow \Theta_{max} \downarrow \Rightarrow$ Instability Shutdown

Simplified Model

Modes with maximum growth rate

$$\mathbf{E}_\mathbf{k} = E_k \delta(k_\parallel - \omega_{pe0}/c)\frac{\mathbf{k}}{|\mathbf{k}|}$$

$$\frac{\partial |\mathbf{E}_k|^2}{\partial t} = 2\gamma_k |\mathbf{E}_k|^2$$

$\gamma_k = 0$ if $k > k_{max}$

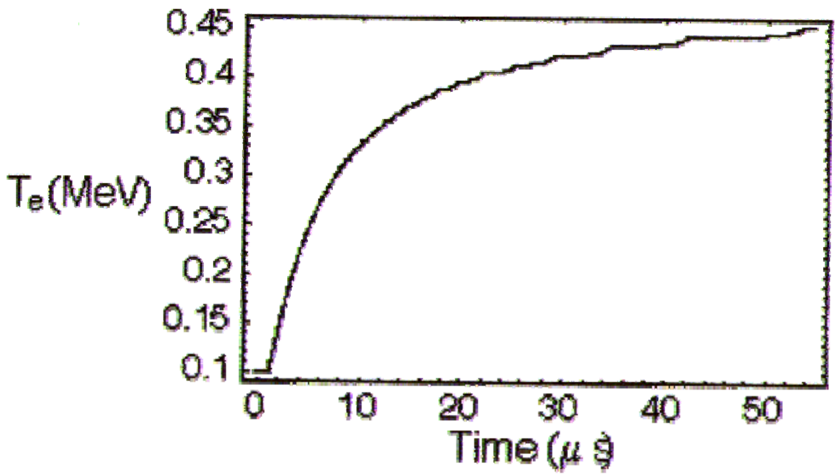
$$\frac{\partial W_{EPW}}{\partial t} = n_e \frac{\partial T_e}{\partial t} = \frac{1}{8\pi}\frac{\partial}{\partial t}\sum_{k \le k_{max}} |\mathbf{E}_k|^2$$

$k_{max} = \omega_{pe0}/v_{th}(T_e)$

Electron Heating

$n_{e0}=10^{29}$ cm^{-3}
$L_{\nu} = 10^{52}$ erg/s
$R_m = 300$ Km
$\langle E_{\nu} \rangle = 10$ MeV
$T_{e0} = 0.1$ MeV

including e-i collisions



$\Delta W_{EPW} \sim 10^{-4} W_{\nu}$

- Preliminary results indicate strong heating up to 0.5 MeV;
- Further analysis is necessary to include relativistic corrections on electron Landau damping - present model overestimates eLD;
- Initial ν_e burst (~ ms) can heat the plasma efficiently;
- Detailed quasi-linear theory for ν's and e's will give signatures of ν-driven instabilities and more accurate results → information to be included in supernovae code
- Stimulated "Compton" scattering must also be considered

Supernovæ explosion and neutrino driven instabilities

e-Neutrino burst

$L_\nu \sim 4\times10^{53}$ erg/s , $\tau \sim 5$ ms

Neutrino emission of all flavors

$L_\nu \sim 10^{52}$ erg/s , $\tau \sim 1$ s

drives plasma waves through neutrino streaming instability

plasma waves are damped (collisional damping)

Due to electron Landau damping, plasma waves only grow in the lower temperature regions

Plasma heating

@ 100-300 km from center

Stimulated "Compton" scattering

Supernova Explosion!

Less energy lost by shock to dissociate iron

Pre-heating of outer layers by short ν_e burst (~ms)

Revival of stalled shock in supernova explosion
(similar to Wilson mechanism)

Anomalous pressure increase behind shock

Neutrino play a critical role in Type II Supernovæ

- **Neutrino spectra and time history of the fluxes probe details of the core collapse dynamics and evolution.**
- **Neutrinos provide heating for “delayed” explosion mechanism.**
- **Sufficiently detailed and accurate simulations provide information on convection models and neutrino mass and oscillations.**

Plasma waves driven by electrons, photons, and neutrinos

Electron beam

$$\left(\partial_t^2 + \omega_{pe0}^2\right)\delta n_e = -\omega_{pe0}^2 n_{e-beam}$$

Photons

$$\left(\partial_t^2 + \omega_{pe0}^2\right)\delta n_e = \frac{\omega_{pe0}^2}{2m_e}\nabla^2 \int \frac{d\mathbf{k}}{(2\pi)^3}\hbar \frac{N_\gamma}{\omega_\mathbf{k}}$$

Neutrinos

$$\left(\partial_t^2 + \omega_{pe0}^2\right)\delta n_e = \frac{\sqrt{2}n_{e0}G_F}{m_e}\nabla^2 n_\nu$$

δn_e Perturbed electron plasma density

Ponderomotive force

physics/9807049, physics/9807050

Kinetic/fluid equations for electron beam, photons, neutrinos coupled with electron density perturbations due to PW

Self-consistent picture of collective e,γ,ν-plasma interactions

Conclusions & Future Directions

In different astrophysical conditions involving intense neutrino fluxes, neutrino driven plasma instabilities are likely to occur

Anomalous heating in SNe II
Electroweak Weibel instability in the early universe
Enhanced Mixing by Turbulent structures

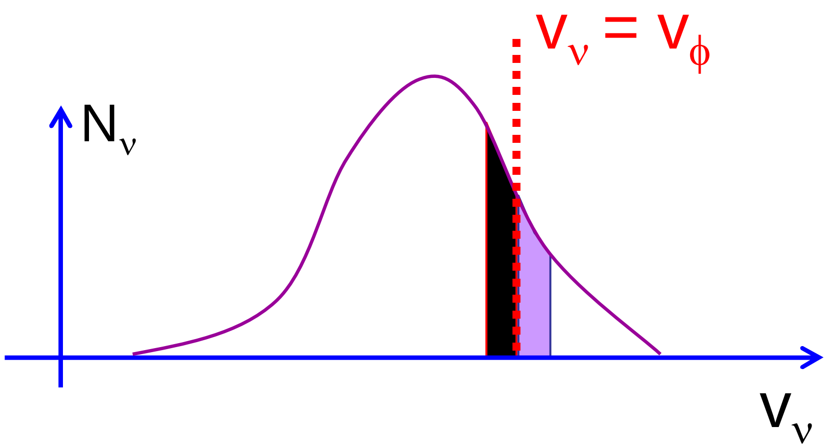
Challenge: reduced description of neutrino driven anomalous processes to make connection with supernovae numerical models

Neutrino Landau Damping I

What if the source of free energy is in the plasma?

Thermal spectrum of neutrinos interacting with turbulent plasma

Collisionless damping of EPWs by neutrinos moving resonantly with EPWs

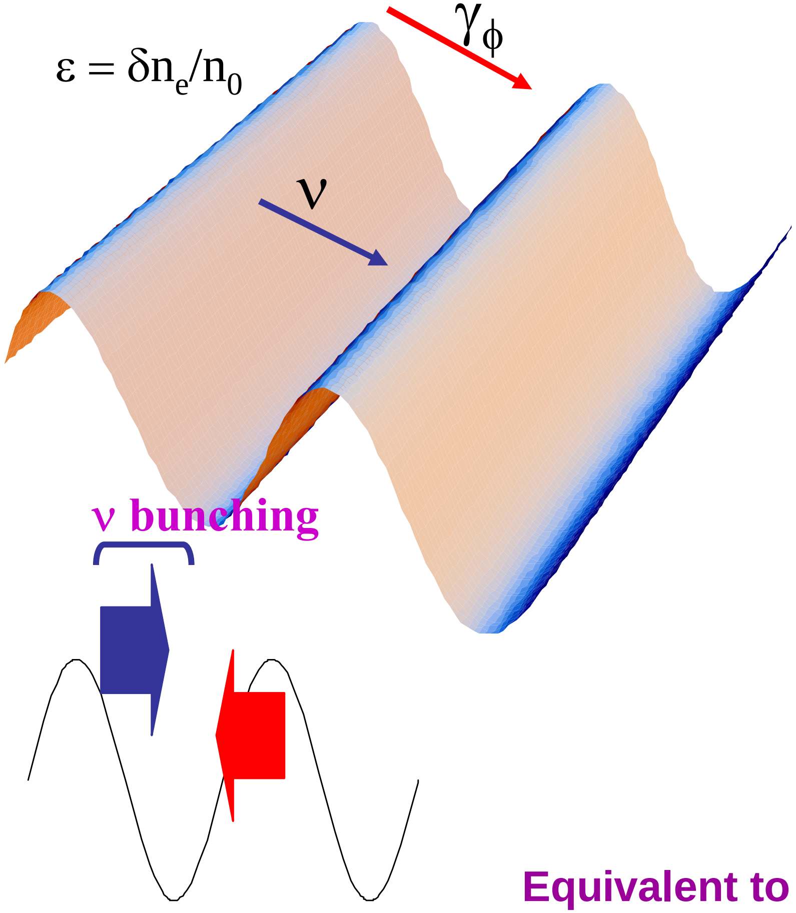


Physical picture for electron Landau damping (Dawson, '61)

General dispersion relation describes not only the neutrino fluid instability but also the neutrino kinetic instability

(Silva et al, PLA 2000)

Neutrino surfing electron plasma waves



$$\left|\Delta E_\nu\right|_{\max} \approx \left|\mathbf{F}\right| L_{dp} \approx 8\sqrt{2} G_F \varepsilon n_{e0}$$

$$\gamma_\phi = 10$$

$$\varepsilon = 10^{-2}$$

$$n_{e0} = 10^{32}\, cm^{-3}$$

$$L_{dp} = \lambda_p \gamma_\phi^2 \approx 3\times 10^{-2}\, cm$$

$$dE_\nu / dL \approx 8\sqrt{2} G_F \varepsilon n_{e0} / (\lambda_p \gamma_\phi^2) \approx 200\, eV / cm$$

Equivalent to physical picture for RFS of photons (Mori, '98)

Neutrino Landau damping II

Neutrino Landau damping reflects contribution from the pole in neutrino susceptibility

$$\chi_\nu(\omega_L, \mathrm{k}_L) \propto \int d\mathbf{p}_\nu \frac{\mathbf{k}_L \cdot \left(\partial \hat{f}_{\nu 0} / \partial \mathbf{p}_\nu\right)}{\omega_L - \mathbf{k}_L \cdot \mathbf{v}_\nu} \longrightarrow \int d\mathbf{p}_\perp \, |\mathbf{p}_\perp| \left\{ P \int \frac{\left(\partial \hat{f}_{\nu 0} / \partial \mathbf{p}_\parallel\right)}{\mathbf{p}_\parallel - \mathbf{p}_{\parallel 0}} d\mathbf{p}_\parallel + i\pi \left(\frac{\partial \hat{f}_{\nu 0}}{\partial \mathbf{p}_\parallel} \right)_{\mathbf{p}_{\parallel 0}} \right\}$$

EPW wavevector $\mathbf{k}_L = \mathbf{k}_{L\|}$ defines parallel direction
neutrino momentum $\mathbf{p}_n = \mathbf{p}_{\nu\|} + \mathbf{p}_{\nu\perp}$
arbitrary neutrino distribution function $f_{\nu 0}$
Landau's prescription in the evaluation of χ_ν

For a Fermi-Dirac neutrino distribution

$$\gamma_{\text{Landau}} \approx -\frac{k_L c}{2} \pi \frac{G_F^2 n_{e0} n_{\nu 0}}{m_e c^2 k_B T_\nu} \left(1 - \frac{\omega_L^2}{c^2 k_L^2}\right)^2 \frac{\mathrm{Li}_2(-\exp E_F / T_\nu)}{\mathrm{Li}_3(-\exp E_F / T_\nu)}$$

Outline

Intense fluxes of neutrinos in Supernovae

Neutrino dynamics in dense plasmas (making the bridge with HEP)

Plasma Instabilities driven by neutrinos

Supernovae plasma heating: shock revival

Neutrino mode conversion (Neutrino oscillations)

Neutrino Landau damping

Neutron star cooling

Solar neutrino deficit

Gamma-ray bursters: open questions

Conclusions

Weibel instability

Free energy in particles (e, i, e^+) transferred to the fields (quasi-static B field)

Fundamental plasma instability

- laser-plasma interactions
- shock formation
- magnetic field generation in GRBs

Signatures: B field + filamentation + collisionless drag

Free energy of neutrinos/anisotropy in neutrino distribution transferred to electromagnetic field

Electroweak Weibel Instability

Usual perturbation theory over kinetic equations + Faraday's and Ampere's law

Cold plasma

$$\left(\omega^2 - k^2c^2\right)\left(1 - \omega\Delta_\nu \phi\left(\hat{f}_{\nu 0}\right)\right) = \omega_{pe0}^2 \qquad \mathbf{k} = k\mathbf{e}_z$$

$$\phi\left(\hat{f}_{\nu 0}\right) = \int d\mathbf{p}_\nu \frac{v_{\nu\perp}}{\omega - kv_{\nu z}} \cos^2\theta \left\{ \frac{\partial \hat{f}_{\nu 0}}{\partial p_{\nu\perp}} + \frac{k}{\omega} v_{\nu\perp} \frac{\partial \hat{f}_{\nu 0}}{\partial p_{\nu z}} - \frac{k}{\omega} v_{\nu z} \frac{\partial \hat{f}_{\nu 0}}{\partial p_{\nu\perp}} \right\}$$

Monoenergetic ν beam ($m_\nu = 0$)

$$\hat{f}_{\nu 0} = \hat{f}_{\nu 0}\left(\mathbf{p}_{\nu\perp}, p_{\nu z}\right)$$

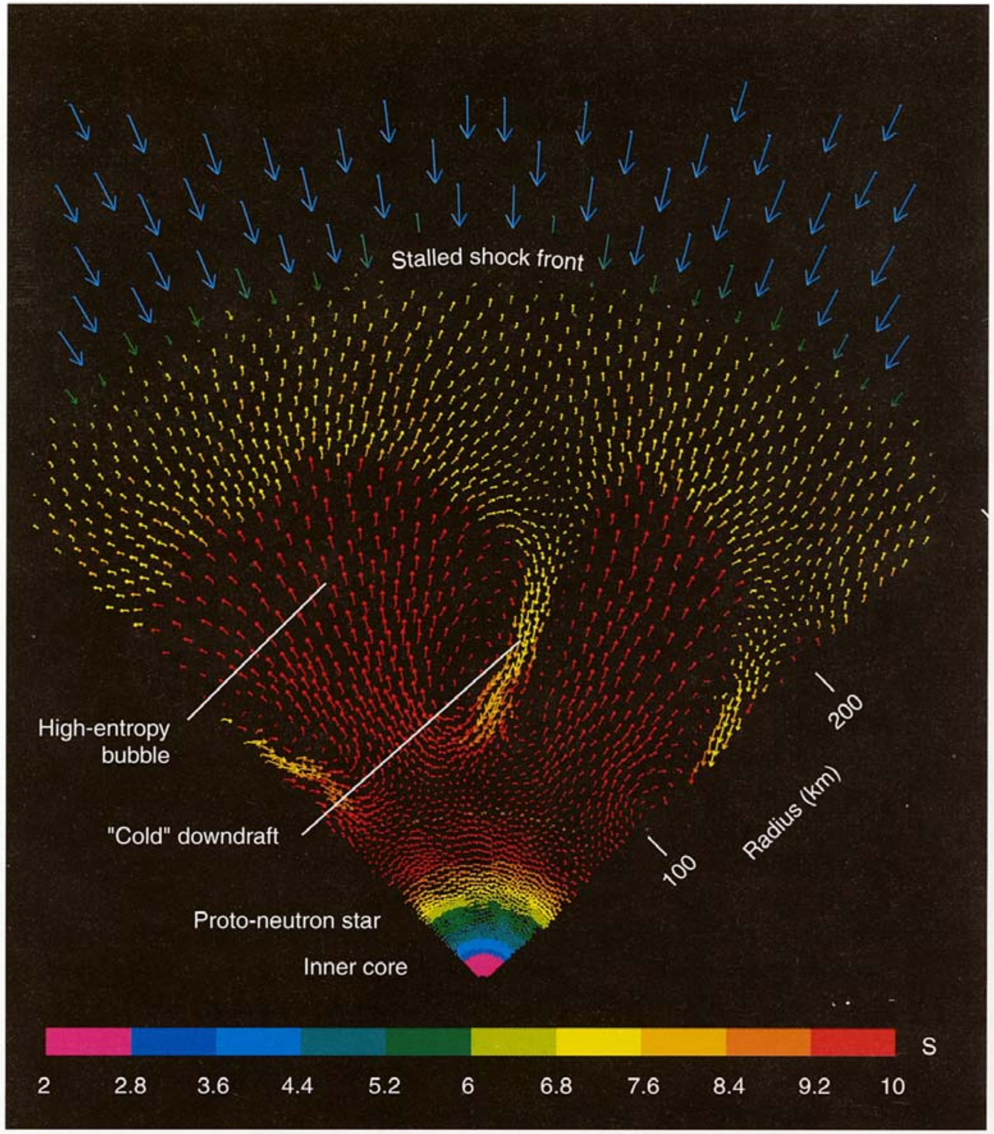
$$\left(\omega^2 - k^2c^2\right)\left(1 + \Delta_\nu \frac{k^2c^2}{\omega^2} \beta_{\nu x 0}^2\right) = \omega_{pe0}^2 \qquad \omega \approx i\gamma_{\mathbf{Weibel}} \;\&\; \left|\gamma_{\mathbf{Weibel}}\right| << |k|$$

$$\gamma_{\mathbf{Weibel}} = \beta_{\nu x 0} \frac{k^2c^2}{\sqrt{k^2c^2 + \omega_{pe0}^2}} \Delta_\nu^{1/2} \quad \propto \quad \mathbf{G_F}$$

(Silva et al, PFCF 2000)

Detailed Simulations

The graphic shows a slice through the core region of a supernova 50 ms after the bounce. Each arrow represents a parcel of matter and the length and direction show velocity (colour represents entropy, S). Regions of higher entropy indicate heating. The shock front is apparent from the position where yellow arrows meet green ones (about 300 km from the core). Low entropy, high velocity material (blue arrows) is the rest of the star raining down onto the core. Neutrinos are present in the blue-green region about 40 km from the core where they are being absorbed in the quasi-static layer which then becomes heated (yellow).



Neutrino Oscillations

MSW – Matter Effect

All neutrinos interact through neutral currents, Z boson.

Only electron neutrinos interact through charge current, W boson.

Refractive index for all flavours

$$N_{\mu,\tau} = 1 + \frac{\sqrt{2}G_F}{p_{\mu,\tau}} f\left(n_e, n_p, n_n\right)$$

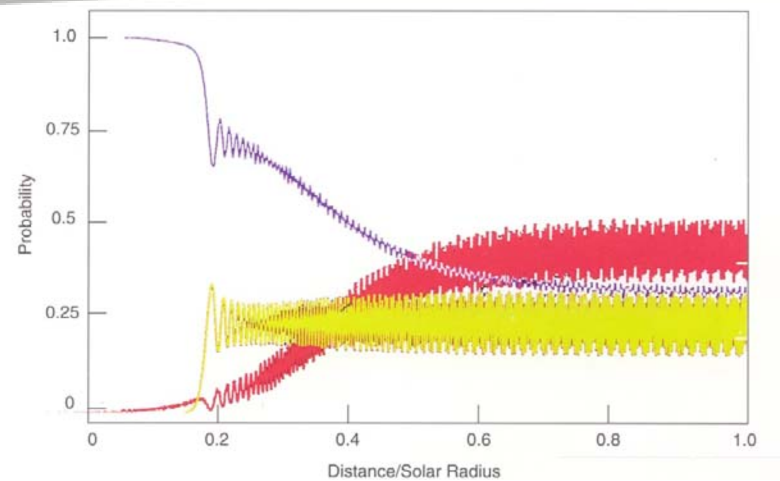
$$N_{\nu_e} = 1 + \frac{\sqrt{2}G_F}{p_{\nu_e}} f\left(n_e, n_p, n_n\right) - \frac{\sqrt{2}G_F}{p_{\nu_e}} n_e$$

Resonance coupling for $p_{\nu_e} = p_{\mu,\tau}$

$$\therefore \Delta m^2 = m^2_{\mu,\tau} - m^2_{\nu_e} = 2\sqrt{2}G_F n_e E_0$$

e.g. in a plasma density gradient

$$L_n = \left(\frac{1}{n}\frac{dn}{dx}\right)^{-1}$$



Probability of detecting a particular flavour of neutrino as they move out from the core through the body of the Sun:- electron neutrinos (purple), muon neutrinos (red), tau neutrinos (yellow).

Conversion probability: Neutrino oscillate

$$C = 1 - \exp\left[-A\frac{\Delta m^2 E L_n}{G_F p^2}\right]$$

Solar data $\Delta m^2 \approx 8.9\text{x}10^{-5}\ \text{eV}^2$

Atmospheric data $\Delta m^2 \approx 2.4\text{x}10^{-4}\ \text{eV}^2$

The MSW effect – neutrino flavor conversion

Flavor conversion – electron neutrinos convert into another ν flavor

Equivalent to mode conversion of waves in inhomogeneous plasmas

$$\frac{d^2\psi_i}{dx^2} + k_i^2\psi_i = 0 \qquad k_i^2 = \frac{E_i^2 - m_i^2c^4 - V_{eff\,i}}{c^2\hbar^2}$$

i = 1, 2, 3 (each ν flavor)

Mode conversion when $k_1 = k_2$, $E_1 = E_2$

$$\frac{d^2\psi_1}{dx^2} + k_1^2\psi_1 = \lambda_1\psi_2$$

$$\frac{d^2\psi_2}{dx^2} + k_2^2\psi_2 = \lambda_2\psi_1$$

$$\lambda_i = \frac{1}{2}\frac{\Delta m^2 c}{\hbar^2}\frac{E_i}{p_i}\sin 2\theta$$

Fully analytical MSW conversion probabilities derived in unmagnetized plasma and magnetized plasma

(Bingham *et al.*, PLA 97, 2002)

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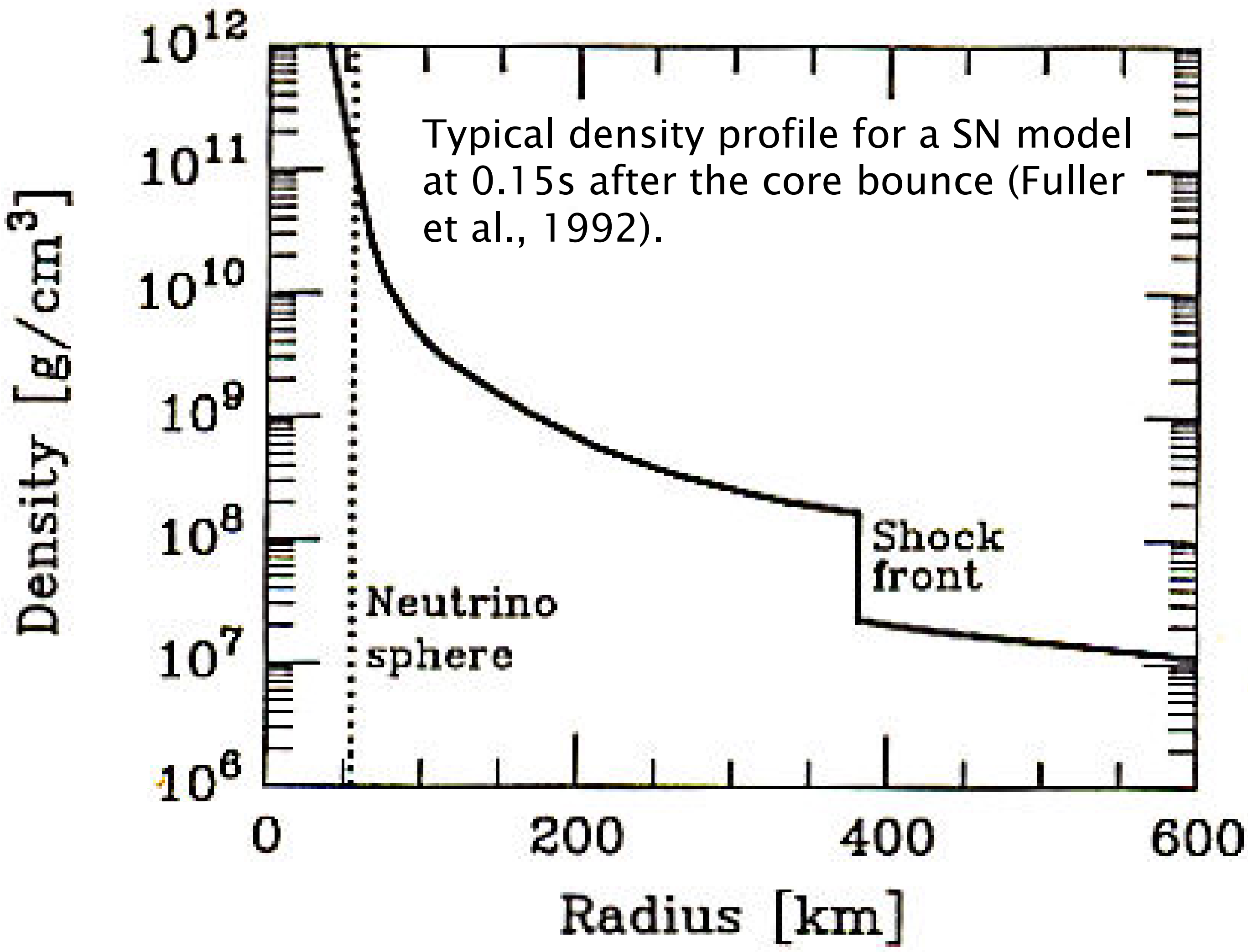
Acknowledgements

- R A Cairns, L O Silva, P K Silva, J T Mendonca, A Serbeto, M Marklund, G Brodin

Typical Density Profile



Length scales

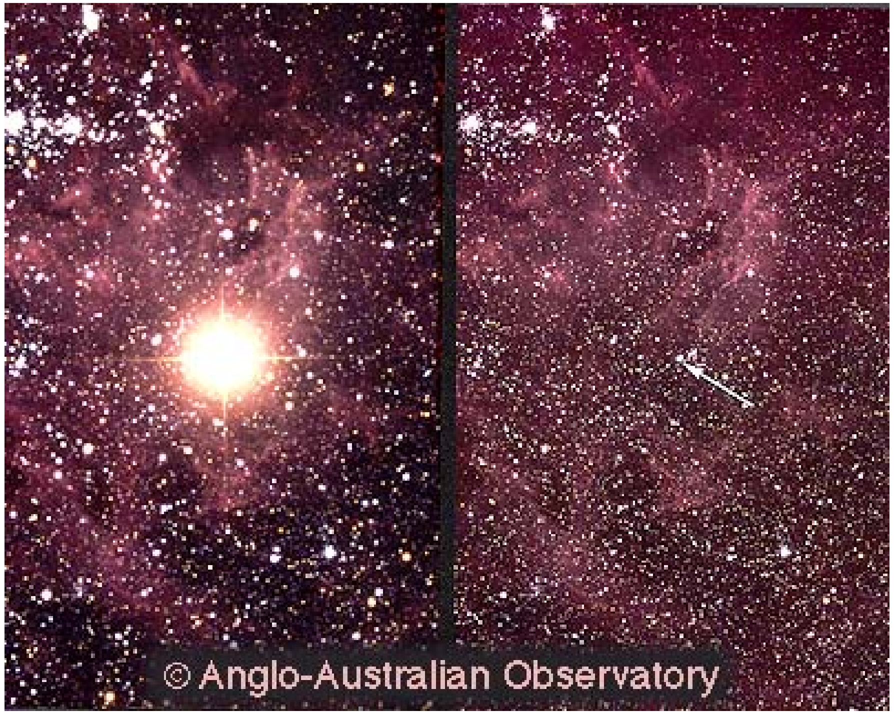
← Compton Scale
HEP

Hydro Scale →
Shocks

Plasma scale
λ_D, λ_p, r_L

Can intense neutrino winds drive collective and kinetic mechanisms at the *plasma scale* ?

Bingham, Bethe, Dawson, Su (1994)



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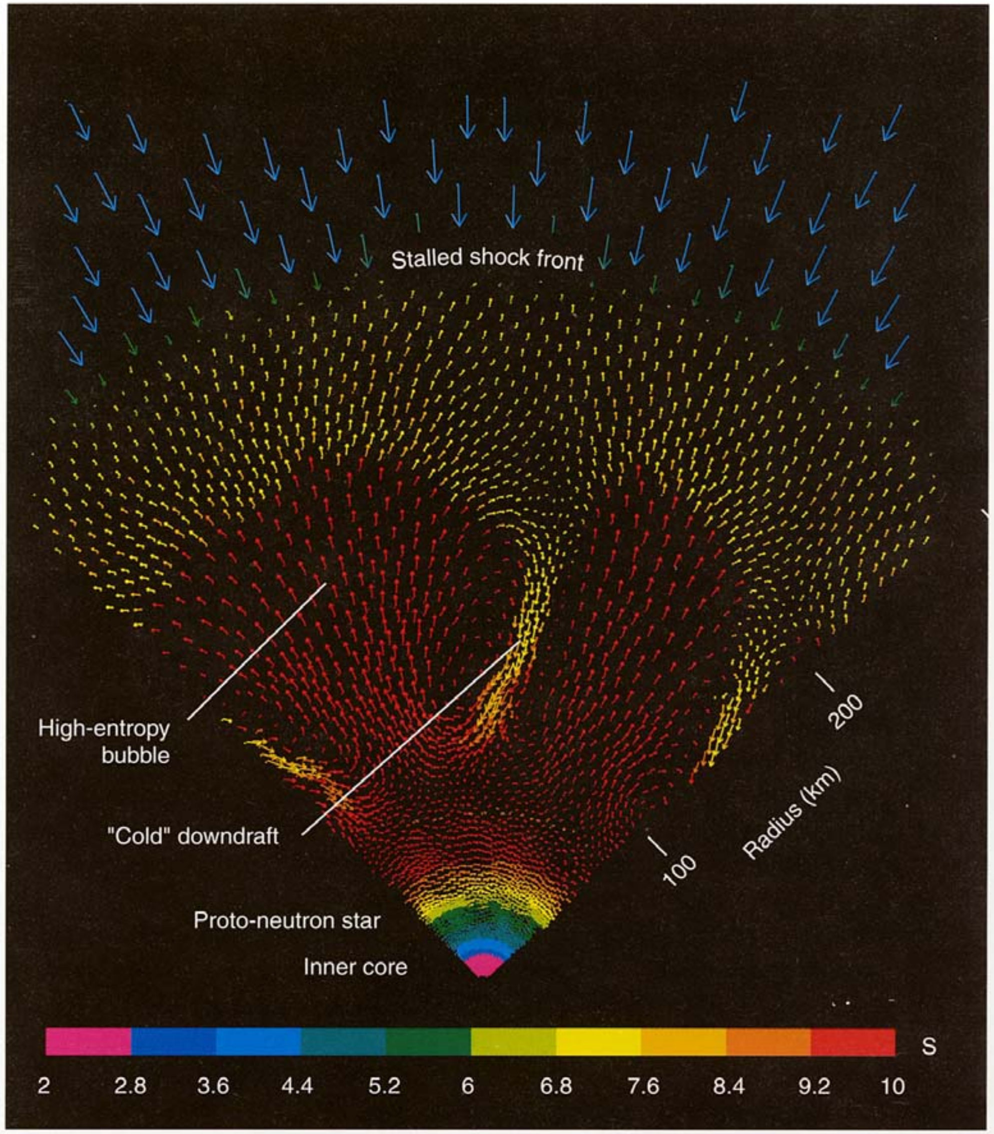
Detailed Simulations

The graphic shows a slice through the core region of a supernova 50 ms after the bounce. Each arrow represents a parcel of matter and the length and direction show velocity (colour represents entropy, S). Regions of higher entropy indicate heating. The shock front is apparent from the position where yellow arrows meet green ones (about 300 km from the core). Low entropy, high velocity material (blue arrows) is the rest of the star raining down onto the core. Neutrinos are present in the blue-green region about 40 km from the core where they are being absorbed in the quasi-static layer which then becomes heated (yellow).



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Anomalous heating by neutrino streaming instability

$$\left(\frac{\Delta E_{\nu}}{10^{50}\,\mathrm{erg}}\right) \approx 1.2 \times 10^{-1} \left(\frac{R}{500\,\mathrm{Km}}\right)^{3} \left(\frac{T}{2\mathrm{MeV}}\right) \times$$

$$\left\{ 0.145 \left(\frac{n}{10^{30}\,\mathrm{cm}^{-3}}\right) + \left(\frac{T}{2\mathrm{MeV}}\right)^{3} \right\}$$

Neutrino heating to re-energize stalled shock $\left(\frac{\Delta E_{\nu}}{10^{50}\,\mathrm{erg}}\right) \approx 1 - 0.1$

Sufficient neutrino energy deposited into electron energy to restart the stalled shock and explode the star.

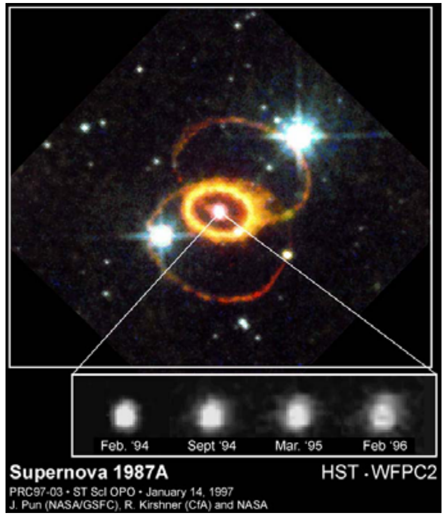
(Silva *et al.*, PoP 2000)

Supernovæ II Neutrinos

- A massive star exhausts its fusion fuel supply relatively quickly.
- The core implodes under the force of gravity.
- This implosion is so strong it forces electrons and protons to combine and form neutrons – in a matter of seconds a city sized superdense mass of neutrons is created.
- The process involves the weak interaction called "electron capture"

$$p^+ + e^- \rightarrow n + \nu_e$$

- A black hole will form unless the neutron degeneracy pressure can resist further implosion of the core. Core collapse stops at the "proto-neutron star" stage – when the core has a ~10 km radius.
- **Problem**: How to reverse the implosion and create an explosion?



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Neutrinos in the Standard Model

Leptons	Electron e Electron neutrino ν_e	Muon μ Muon neutrino ν_μ	Tau τ Tau neutrino ν_τ

An electron beam propagating through a plasma generates plasma waves, which perturb and eventually break up the electron beam

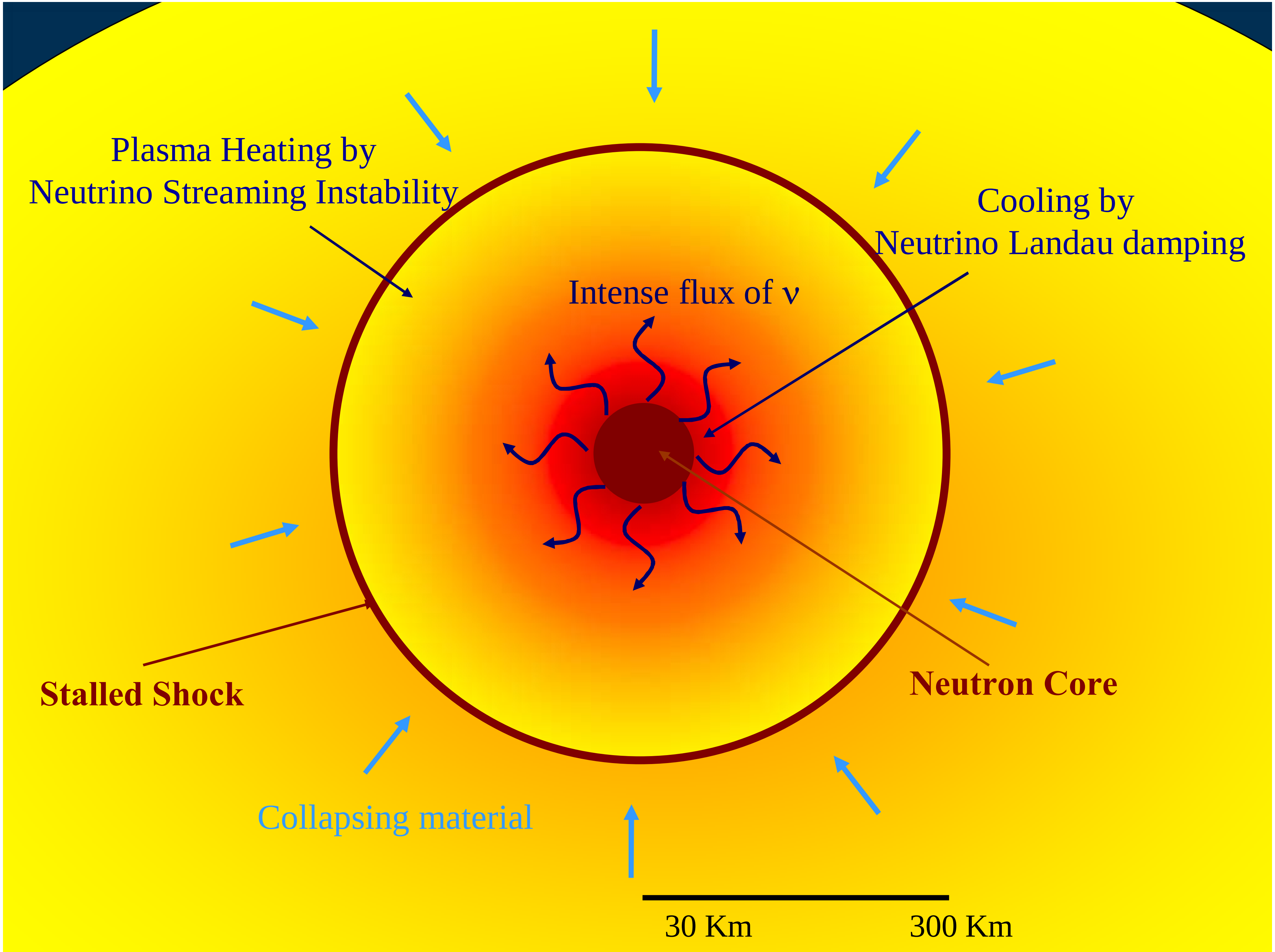
Electroweak theory unifies electromagnetic force and weak force

Electrons and neutrinos interact via the weak force

In a plasma neutrinos acquire an induced charge - dressed particle

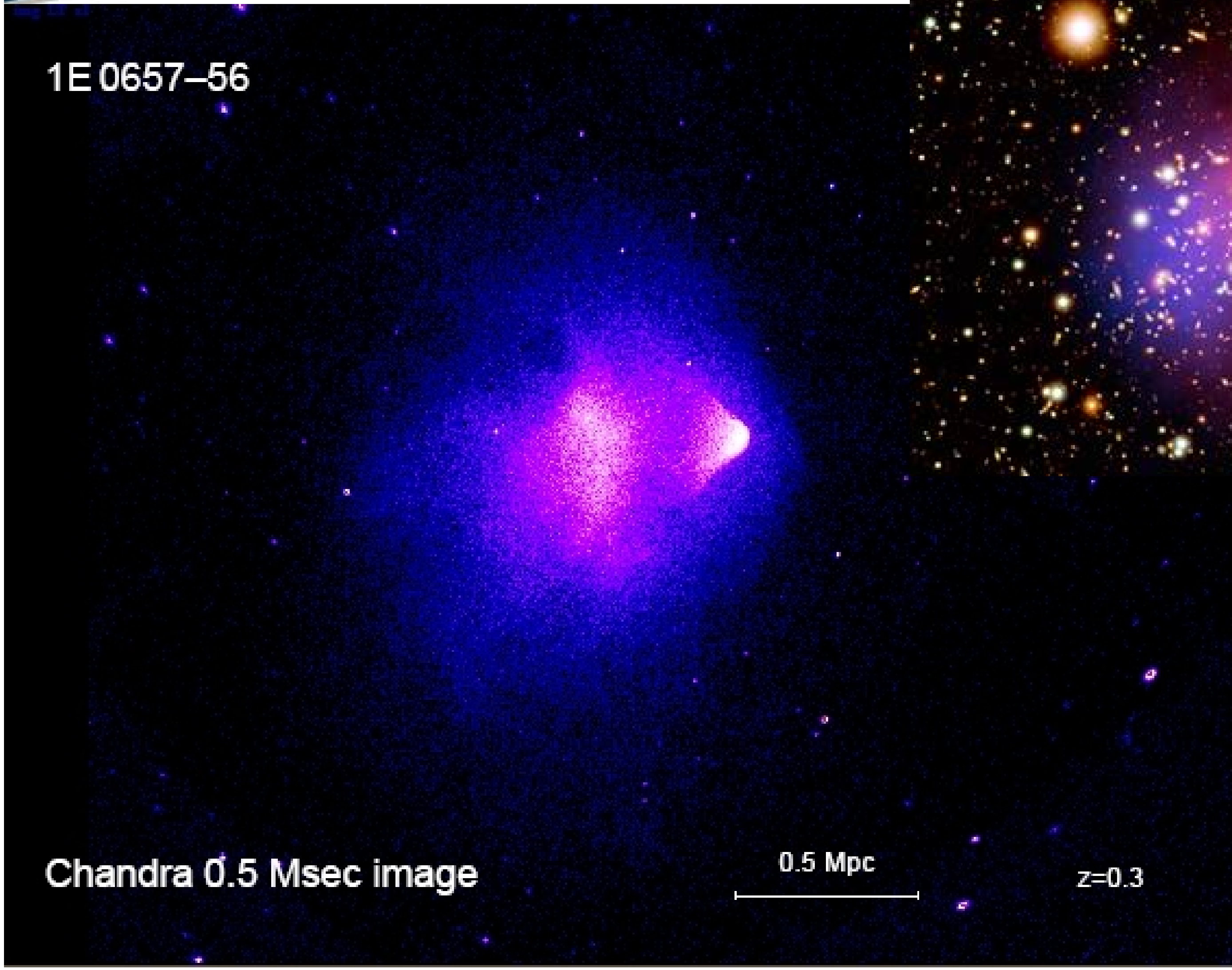
$$e_\nu = -\frac{\sqrt{8}\pi}{k_B T_e} G_F n_{e_0} e_{electron}$$

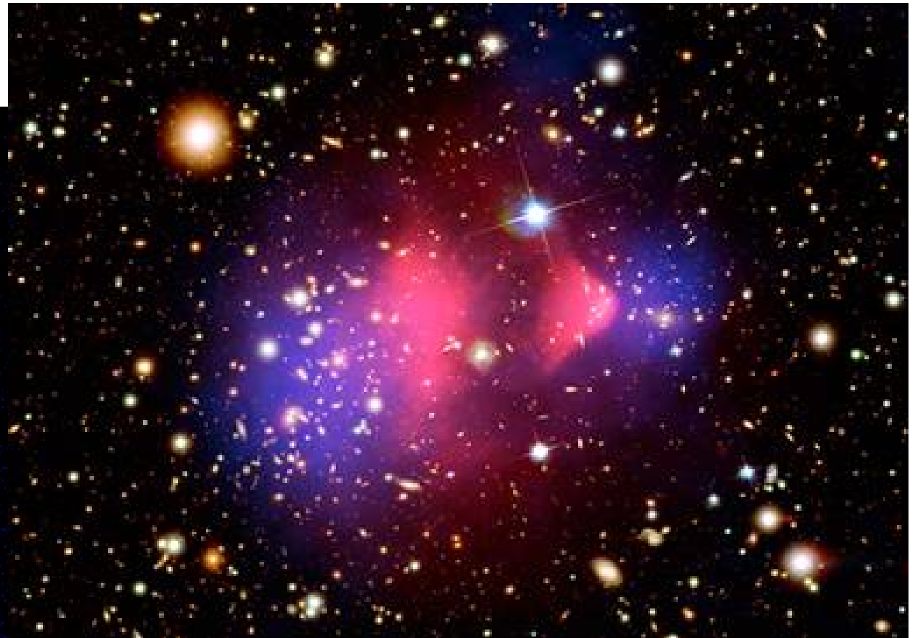
A similar scenario should also be observed for intense neutrino bursts



Plasma Heating by
Neutrino Streaming Instability
Cooling by
Neutrino Landau damping
Intense flux of ν
Stalled Shock
Neutron Core
Collapsing material
30 Km
300 Km

Bullet Cluster





Neutrino Beam-Plasma Instability

Monoenergetic neutrino beam $f_{\nu 0} = n_{\nu 0}\delta(\mathbf{p}_\nu - \mathbf{p}_{\nu 0})$

Dispersion Relation

$$\omega_L^2 = \omega_{pe0}^2 + \left(\frac{m_\nu^2 c^4 \cos^2\theta}{E_{\nu 0}^2} + \sin^2\theta\right)\frac{\aleph k_L^4 c^4}{\left(\omega_L - k_L c\cos\theta \dfrac{p_{\nu 0}c}{E_{\nu 0}}\right)^2}$$

$\theta \equiv \mathbf{k}_L \wedge \mathbf{p}_{\nu 0}$

$$\aleph = \frac{2G_F^2 n_{\nu 0} n_{e0}}{m_e c^2 E_{\nu 0}}$$

¶ If $m_\nu \to 0$ direct forward scattering is absent

¶ Similar analysis of two-stream instability:

- maximum growth rate for $k_L v_{\nu 0\|} = k c \cos\theta \approx \omega_{pe0}$
- $\omega = \omega_{pe0} + \delta = k_L v_{\nu 0\|} + \delta$

Weak Beam $(\delta/\omega_{pe0} \ll 1)$ Growth rate $\gamma_{max} = \dfrac{\sqrt{3}}{2}\omega_{pe0}\left(\dfrac{\tan^2\theta}{\sin^2\theta}\aleph\right)^{1/3} \propto G_F^{2/3}$

Strong Beam $(\delta/\omega_{pe0} \gg 1)$ $\gamma_{max} \propto G_F^{1/2}$

Single ν-electron scattering $\propto \mathbf{G_F^2}$

Collective plasma process much stronger than single particle processes

Big Bang Neutrinos

- The "Big Bang" Model of cosmology predicts that neutrinos should exist in great numbers – these are called relic neutrinos.
- During the Lepton era of the universe neutrinos and electrons (plus anti particles) dominate:
    - ~10^{86} neutrinos in the universe
    - Current density n_{ν} ~ 220 cm^{-3} for each flavour!
- Neutrinos have a profound effect on the expansion of the universe:
    - Galaxy formation
    - Magnetic field generation
    - Dark matter
    - Dark energy

in the early universe

Shukla *et al.*, 1998.
Semikoz *et al.*, 2004.

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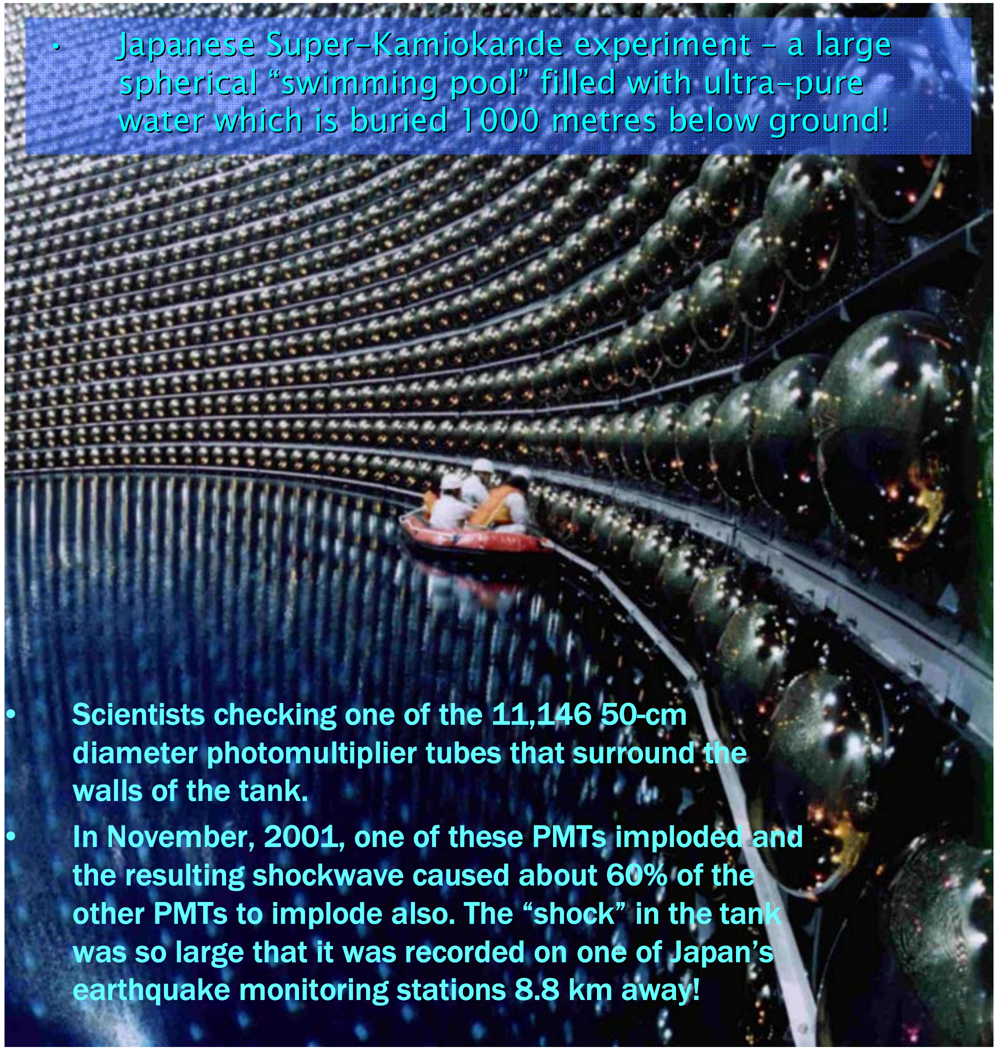
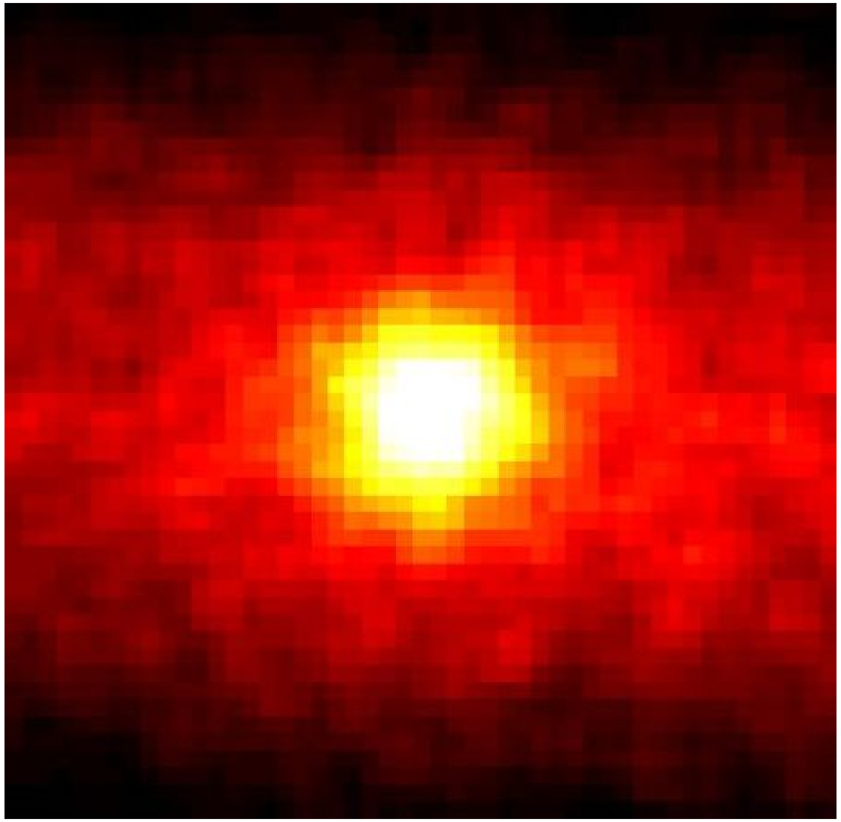
Neutrinos from the Sun – Super-Kamiokande



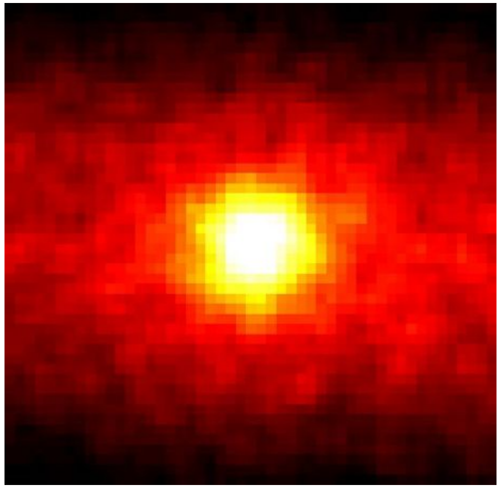
- Japanese Super-Kamiokande experiment – a large spherical "swimming pool" filled with ultra-pure water which is buried 1000 metres below ground!

- Scientists checking one of the 11,146 50-cm diameter photomultiplier tubes that surround the walls of the tank.
- In November, 2001, one of these PMTs imploded and the resulting shockwave caused about 60% of the other PMTs to implode also. The "shock" in the tank was so large that it was recorded on one of Japan's earthquake monitoring stations 8.8 km away!



- Super-Kamiokande obtained this neutrino image of the Sun!

Neutrinos from the Sun



$S = 1.37 \times 10^{6}$ erg/cm^{2}s

Solar Neutrinos

The p-p chain

$$4p + 2e^{-} \rightarrow He^{4} + 2\nu_{e} + 2\gamma + 26.7\text{MeV}$$

3% of the energy is carried away by neutrinos

One neutrino is created for each ≈13 MeV of thermal energy

The "Solar Constant", S (Flux of solar radiation at Earth) is

Neutrino flux at Earth, φ_{ν},

$$\varphi_{\nu} = S / 13 \text{ MeV} \boxed{\approx 6.7 \times 10^{10} \text{ neutrinos/cm}^2\text{s}}$$

These are all electron neutrinos (because the p-p chain involves electrons).

PROBLEM: Only about one-thirds of this flux of neutrinos is actually observed.

SOLUTION: The MSW Effect

Neutrinos interact with the matter in the Sun and "oscillate" into one of the other neutrino "flavours" – Neutrino matter oscillations – electron neutrinos get converted to muon or tau neutrinos and these could not be detected by the early neutrino detectors!

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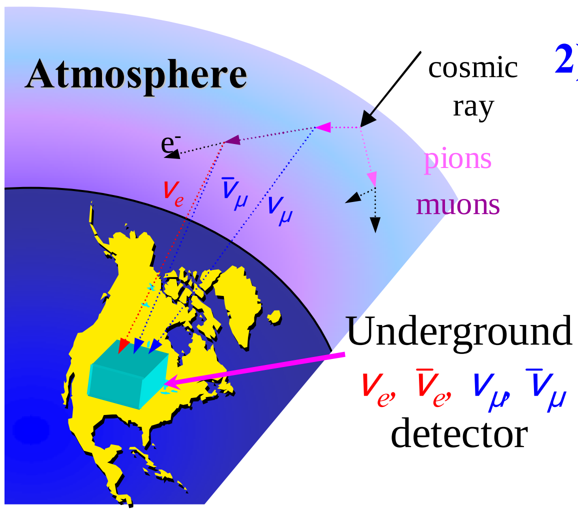
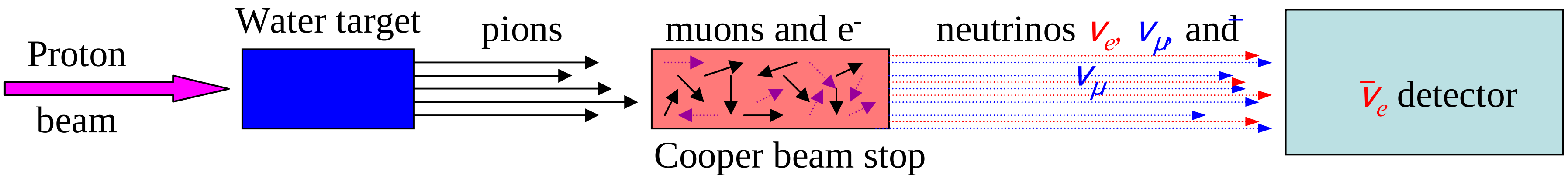
Three Types of Evidence for Neutrino Oscillations

1) Solar neutrinos – a disappearance experiment. The flux of electron neutrinos produced in the Sun's core was measured in large underground detectors and found to be lower than theory predicted. Neutrino oscillations can explain the result – electron neutrinos oscillate into other flavours.



2) Atmospheric neutrinos – a disappearance experiment. Collisions between high energy cosmic rays in the upper atmosphere can create pions. These pions decay into muons which decay into electrons. These decays produce twice as many muon neutrinos as electron neutrinos. However, underground detectors sensitive to both types of neutrinos see a much smaller ration than 2:1. the oscillation of muon neutrinos into tau neutrinos could explain the deficit

3) LSND – an appearance experiment. Positive pions decay at rest into positive muons, which then decay into muon neutrinos, positrons and electron neutrinos. Negative pions decay and produce electron antineutrinos, but the rate is almost negilible. A giant liquid-scintillator neutrino detector located 30 metres downstream looks for the appearance of electron antineutrinos as the signal that the muon antineutrinos have oscillated.

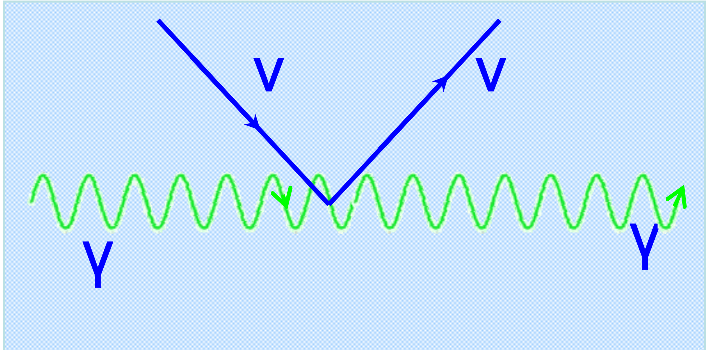


Neutrino Astrophysics

- Neutrino Landau Damping – resonance between neutrinos & plasma turbulence
- Neutrino Cooling: Stellar Evolution, Neutron Star Cooling
    - In dense stellar interiors escaping neutrinos carry off excess energy.
- Kinetic Theory of Neutrino Plasma Coupling

Neutrino Landau Damping

Turbulent Plasma; Relativistic Electron Plasma Waves are resonant with neutrinos ➡ neutrinos damp waves.



- Neutrino Luminosity: $L_\nu = 10^{42}$ ergs/sec
- Interacting with Plasma: $T_e = 10$ keV, $n_e = 10^{28}$ cm^{-3}
- Neutrino Landau Damping Cooling Time: $\tau_c = 10^5$ Yrs
- Compton production of neutrino pairs + photon–neutrino scattering:

$$\tau_c = 10^7 \text{ Yrs}$$

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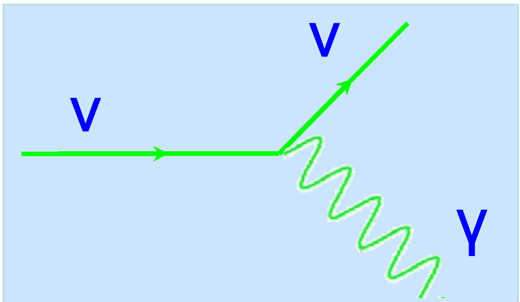
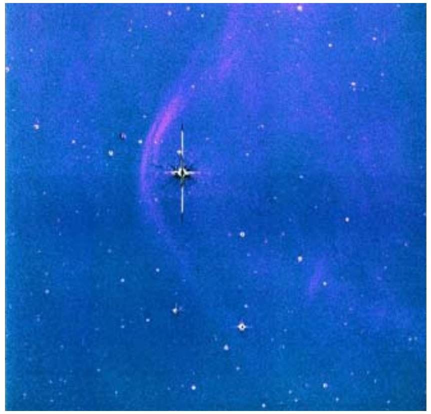
Neutrino Astrophysics

- Magnetic Field Effects:
  - Filamentation Instability — Breaking up of uniform beam of neutrinos
  - Transverse photon emission
    - γ-rays





Pulsar driven bow shock in the interstellar medium

  - New asymmetric ponderomotive force $\propto \underline{P}_\nu \cdot \underline{B}$
    - Radially uniform emission of neutrinos
    - Exerts a macroscopic force
    - The force is in the opposite direction to the magnetic field
    - Can contribute to birth velocity of pulsars

Natural Plasma Laboratories